

THE CRYSTALLIZATION OF A MELT DROPLET CHONDRULE; Gary Lofgren, SN-2 NASA Johnson Space Center, Houston, TX 77058.

More than a decade of experiments (1,2) on the dynamic crystallization properties of melt droplet chondrules has given us a clearer understanding of what controls the development of their textures. The two most important discoveries are (1) that if the droplet has a porphyritic texture it must not have been completely melted and (2) that variations in the number and kind of nuclei can cause a variety of textures to develop from a single composition under very similar cooling conditions. Porphyritic textures, which occur in over 80% of melt droplet chondrules (3), result only if heterogeneous nuclei remain in the droplet during melting and are present when cooling begins. Non porphyritic textures, such as barred, radial, or glassy, result when stable nuclei are eliminated from the melt droplet before it begins to cool. All of the above textures could develop from the same composition cooled at the same rate with small variations in melting temperature or time.

The composition of the chondrule plays a secondary role in determining what textures will crystallize. The melting temperature and phase relations of a given chondrule will be a function of its bulk composition. The melting temperatures of the known chondrule bulk compositions range from approximately 1450°C up to 1650°C (4). Chondrules with lower melting temperatures tend to have pyroxene on the liquidus and those with higher temperatures tend to have olivine. The full range of porphyritic to non-porphyritic textures exists for nearly all the chondrule compositions. The ratio of porphyritic to non-porphyritic textures, however, increases as the olivine content and consequently the melting temperature increases.

To explain how the texture is affected by nucleation and bulk composition, I will follow the crystallization paths of two bulk compositions. The first will have olivine as the liquidus phase and the second, pyroxene. The olivine liquidus chondrule melts at 1600°C (2,5) and the pyroxene liquidus chondrule at 1475°C (6). The precursor of the chondrule will be assumed to be partly crystalline material, but only a small fraction need be crystalline.

To form a melt droplet chondrule, the melt to crystal ratio must be at least 60/40. If melting occurs within 50°C below the liquidus, there will be an even smaller fraction of crystals. These crystals, which act as nuclei, do not have to be optically visible. Crystalline material of sufficient size to be stable and grow can be smaller than the resolution of the optical microscope. This kind of nucleation control of the crystallization textures is no different than what has been determined previously for lunar or terrestrial basalts (7,8).

If the olivine rich chondrule is cooled from the subliquidus temperature range, a porphyritic texture will form. The closer the temperature is to the liquidus, the fewer the nuclei thus the larger the phenocrysts. A microporphyritic texture, which is typical, would require numerous (several per cubic mm), evenly distributed nuclei. The cooling rate will determine the shapes of the phenocrysts which can vary from equant euhedral to elongate skeletal. Typical cooling rates for porphyritic textures would be in the range 2 to 100°C/hr. Faster rates would produce highly elongated, skeletal to dendritic olivines which would still be porphyritic, but are not commonly found in natural chondrules.

If the temperature of melting exceeds the liquidus temperature, stable nuclei will disappear. Over some range of temperatures and times, at or slightly above the liquidus, the melt will contain only subcritical sized nuclei or embryos (9). Embryos will not begin to grow when cooling begins; they must increase in size so that they exceed the critical nuclei radius or the degree of supercooling must increase so that their existing size becomes supercritical, i.e. the critical radius of a nuclei decreases. In either case, some degree of supercooling will develop before growth begins and the degree of supercooling that develops will dictate the shape of the olivine that grows. At the lower degrees of supercooling, acicular skeletal olivines will grow, these are the transition crystal shapes from the porphyritic to the barred olivine (BO) chondrules. As ever fewer and smaller

embryos remain after melting, the degree of supercooling at which the olivines begin to grow will increase and the olivines will become dendritic and then plate dendritic. The plate dendrite is the basic unit of the BO chondrule. The plate or bar width will decrease as the degree of supercooling during growth increases. As the embryos decrease in size, the number of plate dendrites decreases until ultimately a single embryo produces the single plate dendrite of the "classic" BO chondrule. This sequence continues and the next step would be the formation of radial olivine spherulites with continued increase in the degree of supercooling at beginning of growth. Glass will form if nuclei are sufficiently destroyed, although in some olivine rich compositions this requires extremely high temperatures, tens to hundreds of degrees above the liquidus and glasses with no crystals rarely form.

The pyroxene rich chondrule will have a generally similar array of textures as the olivine chondrule when submitted to similar melting and cooling histories relative to its liquidus temperature, but there are some distinct differences. The porphyritic textures, which develop from near subliquidus temperatures, are similar, but the sequence of pyroxene crystal shapes will be slightly different because pyroxene has a different crystal system. The equant euhedral phenocryst gives way to an equant skeletal shape as the cooling rate increases from 5 to 100°C/hr. The pyroxene rich chondrules show a unique behavior, however, not observed in the olivine chondrules. At the slow cooling rate, 5°C/hr, when melting is superliquidus eliminating pyroxene nuclei, olivine will nucleate in its stead and an olivine porphyritic chondrule will form. If pyroxene does eventually nucleate an olivine-pyroxene chondrule will form.

The dendritic and radial pyroxene crystal forms are distinctly different from those in the olivine chondrules. The skeletal pyroxenes become dendritic when nuclei are no longer present and the degree of supercooling at the initiation of growth increases. The dendrites are large with either parallel plates, broadly similar to the BO texture, or more complex tree like dendrites. There is also a significant number of barred and complexly dendritic pyroxene texture types. The transition to radial or spherulitic textures occurs more readily than with the olivine rich compositions presumably because the pyroxene chondrules are more silica rich and pyroxene nucleation more difficult than olivine, thus higher degrees of supercooling can develop during cooling. There is a much wider variety of pyroxene spherulitic forms from the very broad fibers approaching tens of microns to the extremely fine excentroradial textures. The radial pyroxene may enclose olivine phenocrysts which are usually metastable. Because the melting temperature of the pyroxene rich chondrules is lower than the olivine rich chondrules, more of them are melted above the liquidus. Thus a higher percentage are of the radial type than for the olivine chondrules.

Melt droplet chondrules can develop a wide variety of textures with a small variation in the cooling conditions. The mixing of chondrules with different textures which might be presumed to have formed in widely separated locations is unnecessary. The most important variable is the melting temperature. Most melt droplet chondrules are porphyritic and thus the melting temperature cannot have exceeded the liquidus of the individual droplet. The barred, dendritic, and radial textures require slightly superliquidus melting temperatures to form. The melting temperatures of the chondrule precursor material is restricted to a few tens of degrees above or below the liquidus of the individual chondrule.

REFERENCES: (1) Hewins R.H. (1988) in *Meteorites and the Early Solar System* (Kerridge J.F. and Mathews M.S. eds) 660-679. (2) Lofgren G.E. (1989) *Geochim Cosmochim Acta* 53, 461-470. (3) Gooding J.L. and Keil K. (1981) *Meteoritics* 16, 17-43. (4) Radomsky P.M. and Hewins R.H. (1988) *Meteoritics* 23, 297-298. (5) Lofgren G.E. and Lanier A.B. (1988) *Meteoritics* 23, 285. (6) Lofgren G.E. and Russell W.J. (1986) *Geochim Cosmochim Acta* 50, 1715-1726. (7) Lofgren G.E. (1980) in *Physics of Magmatic Processes* (Hargraves R.B. ed.) 487-551. (8) Lofgren G.E. (1983) *J. Petrol.* 24, 229-255. (9) Turnbull D. (1950) *J. Chem. Phys.* 18, 198-203.